Bi-directional DC/DC converter topology comparison and design

HEV/EV and server applications

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Zhong Ye
Agenda

• Application overview and specifications
  o Automotive application
  o Server and Datacenter

• Topology comparison
  o Four-phase interleaved fixed frequency Bi-directional Buck converter
  o Four-phase interleaved ZVS transition-mode Bi-directional Buck converter

• UCD3138-based control scheme and implementation

• Test data comparison
  o Switching waveform comparison
  o Efficiency comparison
  o Loss Breakdown Comparison
  o Thermal
  o EMI

• Conclusions
Application overview—automotive

Today: 12-V system

- Continuous increase of electrical power consumption
- 12-V system running into limitations
- Improve efficiency for high-power loads (AC comp., pumps, …)
- Mild hybrid functionality asking for high cycling performance (lead acid not good fit for more recuperation)
- Additional savings due to intelligent networks (partial shutdown loads in the network)
- Reduce copper diameter and cost

Next step: 48-V power network extension

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48-V / 12-V electrical system with start/stop

Parts using 48 V

- Transmission oil/fluid pump
- AC compressor
- Water pump
- Cooling fan
- Fuel pump
- Active suspension control
- 48-V / 12-V bi-directional DC/DC converter
- 48-V Li-Ion battery management
- Electric power steering
- 48-V traction motor inverter

12-V electrical system
12-V battery

12-V system
12-V battery

48-V / 12-V system
48-V Li-Ion battery management

48-V / 12-V bi-directional DC/DC converter

48-V / 12-V system
48-V Li-Ion battery management

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48-V / 12-V system
48-V Li-Ion battery management
Typical 48-V / 12-V converter specification for automotive

- >96 percent efficiency
- No air or liquid cooling needed
- Multi-phases interleaved
- Phase current sharing
- Can be stacked to deliver 3 kW (3-kW buck-mode and 800-W boost-mode)
- 12-V reverse connection prevention
- Failed phase isolation
- Auto phase-shedding and offset for light-load management
- Protection including OCP, OVP, OTP
- 70 V/100 ms load-dumping BN48 surge
- 100 uA quiescent current when disabled (after 48 V is disconnected)
- CAN bus or SPI communication
Other applications: data centers and servers

Advantages of local energy storage data center deployments

- Reduce cost up to 5 times
- Eliminate up to 9% losses associated with UPS
- No requirement for a UPS or battery room
  - 25% facility footprint reduction
- Improve serviceability significantly
  - Hot-swappable
  - Minimize potential failure impact zone

* Reference from Microsoft Publication
## Topology investigation

<table>
<thead>
<tr>
<th>PROS</th>
<th>Transition-mode ZVS DC/DC (sync-buck) converter</th>
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<tbody>
<tr>
<td>Hard-switching, non-Isolated DC/DC (sync-buck) converter</td>
<td>• Simple control</td>
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<tr>
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<td>• Fixed-frequency</td>
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<tr>
<td></td>
<td>• Low inductor current ripple</td>
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<tr>
<td></td>
<td>• Soft-switching, potentially high efficiency</td>
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<td>• Low common-mode noise</td>
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<th>CONS</th>
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<td></td>
<td>• High-switch ringing</td>
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<td></td>
<td>• High common-mode noise</td>
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<td>• High inductor current ripple</td>
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<td>• Variable frequency</td>
</tr>
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<td>• Complex control</td>
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</table>
Hard-switching and soft-switching bi-directional converter

Hard-switching converter

Buck-mode

Soft-switching converter

Boost-mode

Energy transfer direction
UCD3138 overview

Key features

- Multi-nested loop isolated digital controller
- 3 loop with 14-bit DAC reference
- 2-pole 2-zero PID filters with multi-coeff banks
- PWM, phase-shift and resonant-mode control
- Constant voltage, current and power modes
- Input voltage feed-forward and Vpri-sensing
- Peak current mode with internal slope comp.
- Cycle-by-cycle current limit with CLF counter
- 8x over sampling or averaging at EADC
UCD3138 key features (cont.)

- 12-bit ADCs with hardware filters
- 12-bit ADCs with dual hold-sampling
- Auto PWM-LLC and PWM-PS mode switching
- Burst-mode for light load operation
- Integrated copper trace current-sensing
- Integrated current-sharing circuit
- 8 high resolution DPWM outputs (250 ps)
- 32-bit, 32-MHz ARM 7 (32 KB PFlash, 4 KB DFlash)
- Multi-channel, 12-bit 256 ksp/s GP ADC
- On-chip (BOD / POR)
- Single-supply operation (3.3 V)

- Single supply operation (3.3 V)
- On-chip reference + oscillator
- 2 UART’s + programmable PMBus interface
- 2 MHz max switching frequency
- 4 ns frequency resolution
- External interrupt + fault input and output
- –40°C to +125°C extended temp range
- 64 pin and 40 pin QFN packages
- Power-saving features
- And MORE!!!
UCD3138-based control

- Three control loops: current loop, 12-V voltage loop, 48-V voltage loop
- Total current is sensed for current loop control
- Current source operation before voltages reach set points
- Phase currents are sensed for current balance
- Current command set by digital communication port or ADC input

Additional control for ZVS operation:
- Phase 1 negative current sensed
- Negative current thresholds programmed by PWM0, one to generate a sync signal
- Sync signal controls frequency modulation
Current ripple and phase number selection

- Duty cycle directly determines phase number selection
- Optimal phase numbers for 48-V /12-V buck and boost power conversion are: 4, 8, 12
- Adding phases reduces current ripple further when duty cycle is away from:
  - 0.25 in buck-mode
  - 0.75 in boost-mode
System block diagram for circuit test

Phase 1 (Master)

Phase 2

Phase 4

Connect to 4 phases of Buck/Boost

Programmable negative current limit and cycle-by-cycle control
### Power stage component selection and design

<table>
<thead>
<tr>
<th></th>
<th>Hard-switching</th>
<th>Soft-switching</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switching frequency</td>
<td>140 kHz</td>
<td>100 kHz- 450 kHz</td>
</tr>
<tr>
<td>Current ripple at full load</td>
<td>16.25 A (±25% ripple)</td>
<td>65 A</td>
</tr>
<tr>
<td>Inductor value</td>
<td>4.7 uH</td>
<td>1.4 uH</td>
</tr>
<tr>
<td>Inductor DC resistance</td>
<td>1.86 mΩ</td>
<td>0.618 mΩ</td>
</tr>
<tr>
<td>Inductor part number</td>
<td>SER2915H-472KL (Coilcraft)</td>
<td>Litz wire: AWG# 32, 110 strands PQ26/20 core -TDK B65877B0000R097</td>
</tr>
<tr>
<td>Inductor photos</td>
<td><img src="image" alt="Inductor Photos" /></td>
<td><img src="image" alt="Inductor Photos" /></td>
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## Power stage component selection and design (cont)

<table>
<thead>
<tr>
<th>Component</th>
<th>Hard-switching</th>
<th>Soft-switching</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main MOSFETs</td>
<td>Infineon IPB017N100N5: 100 V, 1.7 mΩ</td>
<td>Infineon IPB015N08N5: 80 V, 1.5 mΩ</td>
</tr>
<tr>
<td>Reverse protection FETs</td>
<td>CSD16556Q5B: TI, 20V, 1.062 mΩ @ 75ºC</td>
<td>CSD16556Q5B: TI, 20 V, 1.062 mΩ @ 75ºC</td>
</tr>
<tr>
<td>48-V fuses</td>
<td>Littlefuse: 0891030 30A, 2.06 mΩ @ 25ºC, 2.18 mΩ @ 90ºC</td>
<td>Littlefuse: 0891030 30 A, 2.06 mΩ @ 25ºC, 2.18 mΩ @ 90ºC</td>
</tr>
<tr>
<td>Low inductance shunt-sensing resistor</td>
<td>Panasonic ERJ-M1WTF2M0U: –2 mΩ</td>
<td>Panasonic ERJ-M1WTF2M0U: –2 mΩ</td>
</tr>
<tr>
<td>48-V input filter inductor</td>
<td>Coilcraft XAL1580-102 MEB: 1 uH 73.5 A, 0.93 mΩ typical</td>
<td>Coilcraft XAL1580-102 MEB: –1 uH 73.5A, 0.93 mΩ typical</td>
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</table>
Bi-directional DC/DC converter prototype 110 A
ZVS buck-switching waveform

- Max frequency = 450 kHz
- Min frequency = 104 kHz
Buck-switching waveform comparison 20 A

- Hard switching
  - 6V overshoot

- Soft-switching: negative current and ZVS
  - No overshoot
  - Soft on/off edges

- Deadtime from SyncFET turn-off to main FET turn-on = constant 220 nS
- Deadtime from main FET turn-off to sync FET turn-on varies based on Io
Buck switching waveform comparison 110 A

Hard switching (140 kHz)

Soft switching: Negative current and ZVS (104 kHz)

- Deadtime from sync FET turn-off to main FET turn-on = constant 220 nS
- Deadtime from main FET turn-off to sync FET turn-on varies based on Io
Boost-switching waveform comparison 20 A

Hard-switching (140 kHz)
- Deadtime from sync FET turn-off to main FET turn-on 37.5 nS
- Deadtime from main FET turn-off to sync FET 37.5 nS

Soft-switching: Negative current and ZVS (353 kHz)
- Deadtime from SyncFET turn-off to Main FET turn-on = constant 220 nS
- Deadtime from Main FET turn-off to SyncFET turn-on varies based on Io
Boost-switching waveform comparison 110 A

Hard-switching (140 kHz)
- Deadtime from sync FET turn-off to main FET turn-on = 37.5 nS
- Deadtime from main FET turn-off to sync FET = 37.5 nS

Soft-switching: Negative current and ZVS (104 kHz)
- Deadtime from sync FET turn-off to main FET turn-on = constant 220 nS
- Deadtime from main FET turn-off to sync FET turn-on varies based on Io

3V overshoot

8V overshoot

Hard switching

Soft on/off edges
Bi-directional operation

Programmable parameters

- 12-V battery current at buck- and boost modes
- Current ramp-up and ramp-down time
- Idle time between buck and boost operation
- 48-V and 12-V battery OVP and UVP thresholds
GUI control screen

Device GUI for circuit configuration and debug

- Facilitate firmware and hardware debug
- Change parameters while circuit is running
- Monitor register values firmware execution
- Converter status reporting

Control GUI for system test and monitoring

- Facilitate system test
- Ease system parameter setting
- Monitor system operating state and status
- Monitor battery voltage and phase currents
Loss breakdown chart at 110 A, 12-V output

*Calculated data with test data recertification
Efficiency comparison: buck-mode

- ZVS Buck
- Hard Switching Buck
- ZVS Buck w/o safety parts
- HS Buck w/o safety parts

<table>
<thead>
<tr>
<th>12 V Current / A</th>
<th>Efficiency</th>
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<tr>
<td></td>
<td>84.00%</td>
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<tr>
<td></td>
<td>86.00%</td>
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<td></td>
<td>88.00%</td>
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<td>96.00%</td>
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<td>98.00%</td>
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Efficiency comparison: boost-mode

Mode-switching and phase-shedding can improve light-load efficiency.
Light-load management (LLM)

- DCM operation improves efficiency by around 2% at 10 A load, compared with CCM operation.
- Ideal diode emulation (IDE) can further improve light-load efficiency (by around 0.3%-0.7%).
- Phase-shedding can be used to improve light-load efficiency when switching loss becomes dominant.
- Mode switching needed for LLM:
  - CCM → DCM/IDE → phase-shedding
  - ZVS transition-mode → DCM/IDE → phase-shedding

[Diagrams showing voltage and current waveforms for DCM control (buck-mode) and ideal diode emulation (boost mode).]
Thermal data comparison 110 A

Hard-switching buck-mode

<table>
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<tr>
<th>Component</th>
<th>Hard-switching</th>
<th>ZVS buck-mode</th>
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</thead>
<tbody>
<tr>
<td>Top FET / °C</td>
<td>84.75/92</td>
<td>72.0/73*</td>
</tr>
<tr>
<td>Bottom FET / °C</td>
<td>68.25/69</td>
<td>61.5/64</td>
</tr>
<tr>
<td>Core / °C</td>
<td>64/65</td>
<td>56.5/59</td>
</tr>
<tr>
<td>Winding / °C</td>
<td>77.5/78</td>
<td>62.3/64</td>
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</tbody>
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*Avg. temp / max temp

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Thermal data comparison 110 A

Hard-switching boost-mode

ZVS boost-mode

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<th>Winding / °C</th>
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<tr>
<td>67.25/72</td>
<td>75.25/77</td>
<td>63/64</td>
<td>69.25/73</td>
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*Avg. temp / max temp

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<th>Top FET / °C</th>
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<tr>
<td>64.3/66*</td>
<td>75.3/76</td>
<td>65/66</td>
<td>66.75/71</td>
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EMI floor and bias noise (quasi-peak)
EMI comparison (quasi-peak)
Hard- versus soft-switching at buck-mode and full-load

Class 5 Avg

15 dB

Class B QP

Soft-switching

Hard-switching
## Summary and conclusions

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<th>Hard-switching</th>
<th>Soft-switching</th>
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<tr>
<td>Efficiency</td>
<td>Better efficiency at light-load range</td>
<td>Better efficiency potential at heavy loads</td>
</tr>
<tr>
<td>Voltage spike, dv/dt and current ripple</td>
<td>Higher voltage spike and dV/dt but lower current ripple</td>
<td>Softer dv/dt and lower voltage spike, but much higher current ripple</td>
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<tr>
<td>Control complexity</td>
<td>Fixed frequency, less complexity</td>
<td>Hardware is required for cycle-by-cycle phase synchronization</td>
</tr>
<tr>
<td>Thermal</td>
<td>Higher FET temperature rise</td>
<td>Lower temperature rise and less than 75°C FET case temperature and windings</td>
</tr>
</tbody>
</table>

- One power stage designed for both hard- and soft-switching converter comparison tests
- Efficiency advantage of soft-switching at heavy load is insignificant
- Soft-switching converter can improve efficiency by optimizing inductor design
- Light-load management can improve light-load efficiency to a similar level for both controls
- EMI under 1 MHz has insignificant difference, but soft-switching exhibits up to 15 dB lower noise at higher frequency
- UCD3138 is capable of doing both hard-switching and soft-switching control
- GUI eases circuit debug and facilitates system test and monitoring
Backup Slides
Bi-directional operation 100 A

Hard-switching buck-boost with current ramping up / down

Hard-switching buck-boost with no soft off

ZVS buck-boost with no soft off

Programmable parameters
- 12-V battery current at buck-mode and boost-mode
- Current ramp-up and ramp-down time
- Idle time between buck and boost operations
- 48-V and 12-V battery OVP and UVP thresholds
UCD3138 hardware-based frequency modulation

- Sync resets master phase DPWM counter
- Sync FET is turned at Event4
- Active FET is turned on at Event1
- All deadtimes maintain unchanged
- All phases are synchronized by hardware
- All slave phases follow master phase automatically
- Slave phase offset is adjusted by firmware periodically

![Diagram of frequency modulation](attachment:image_url)
8-phase control
Power system migration

Opportunities by introducing a new voltage level. Displacement of high-power loads.

Displacing all high-power loads and implementation of new high-power functions can reduce the requirements to the DC/DC converter and the 12-volt battery significantly.

Terminology

- CRAC: computer room air conditioner
- adiabatic AHU: air-handling unit
- ADC
- PWM
- DPWM
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